UCRL-JC-122170
PREPRINT

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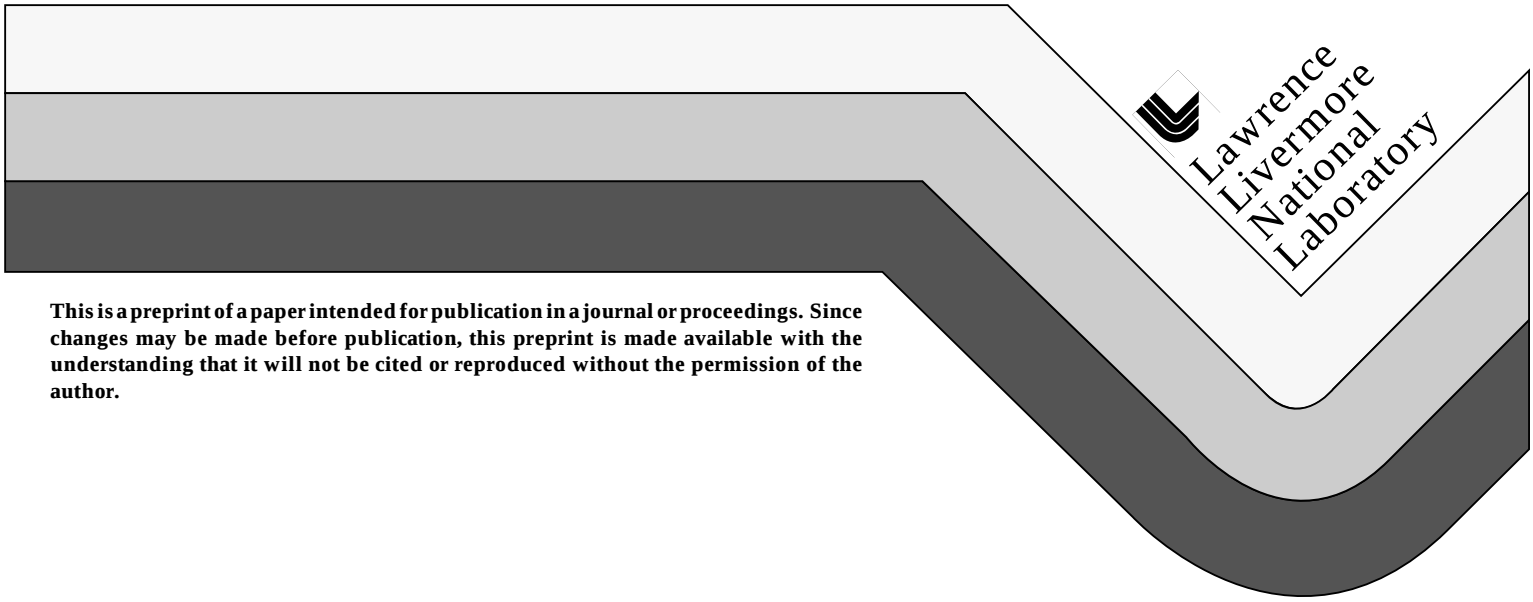
**This paper was prepared for submittal to the
AIRAPT Conference
Warsaw, Poland
September 11–15, 1995**

September 12, 1995



SHOCK WAVE MEASUREMENTS

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Much of our knowledge of the properties of matter at high pressures, from the static ruby pressure scale to shock compression at Gbar pressures, rests ultimately on the use of shock waves. Simple conservation relations define the initial and final states, leading to absolute measurements. I will describe some methods for measuring the equation of state of materials under shock loading for a variety of methods of shock production, and also describe the basis for other optical methods used widely in shock physics.

1 Introduction

The ubiquitous use of shock waves in high pressure physics may be due to the fact that shock waves are easy to generate, but more importantly because the final state of the shocked material can be determined absolutely through measurement of the initial conditions and kinetic variables. The Rankine-Hugoniot relations express the conservation of momentum, mass, and energy:

$$P - P_0 = \rho_0 u_s u_p \tag{1}$$

$$\rho = \rho_0 \left(1 - \frac{u_p}{u_s}\right)^{-1} \tag{2}$$

$$E - E_0 = \frac{1}{2}(P + P_0)(V_0 - V) \tag{3}$$

where P, ρ, E refer to the final shock pressure, density, and internal energy; $P_0, \rho_0 \equiv 1/V_0, E_0$ are the initial pressure, density, and energy, respectively. The propagation velocity of the shock is u_s, and the velocity of the material behind the shock, the mass velocity, is u_p. Measurement of ρ_0, and any two of the variables P, E, ρ, u_s, u_p determine the final shock state. In practice, it is easiest to determine u_s and u_p; this paper describes methods for these measurements for a variety of typical shock environments.

We will describe temperature measurements, for we note that Eq. 3 only gives the change in total energy, and the partition function for its distribution among the internal and external degrees of freedom is unspecified. Temperature measurements have proven invaluable in studies of phase changes and deserve special treatment. A large body of work has also developed using a variety of electrical gauges embedded in, or adjacent to, the materials of interest. I've chosen not to discuss these in this brief report, and refer the interested reader to other sources.[1] In fact, the scope of shock measurements is so broad that only a sketch of the field can be attempted here.

Before describing the measurement techniques, a brief description of shock generation methods is in order. These divide naturally into impact and ablation methods. In the impact method, a plate of material is made to impact onto another at high velocity, producing a shock wave. Both high explosive and gun techniques are in this class. In the ablation method, a sample of material is rapidly heated to a very high temperature. This causes the material to expand rapidly into the surrounding material, producing a shock wave. Lasers and nuclear explosions are examples of this method of shock generation. The ablation methods are capable of achieving the highest pressures, while impact experiments generally offer the greatest opportunity for high absolute accuracy. In this paper, I will limit my discussion to impact experiments, since the methods for ablatively driven experiments are more challenging to perform (and to describe!), and are still under development.

2 Measurements of u_p

When a shock passes from one material to another, the pressure and mass velocity are continuous across the interface. In the simplest impact experiment between identical materials, the mass velocity of the generated shock is just $u_p = u_i/2$, where u_i is the impactor velocity. So a precise measurement of the impactor velocity allows us to find u_p easily. This is usually accomplished using flash x-radiography[2], lasers, or magnetic coils to find the time required for the projectile to traverse a known distance. This quantity can be measured

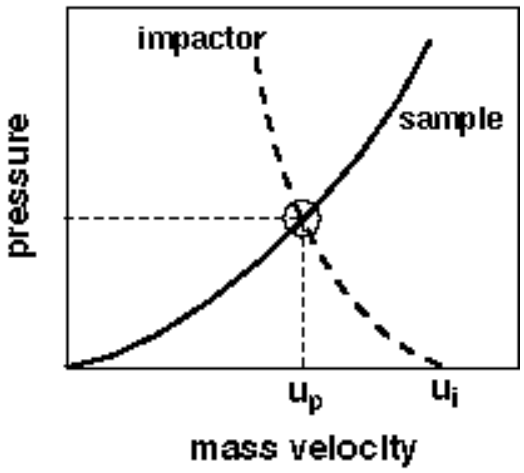

Figure 1: Finding the value of u_p for an impact of dissimilar materials using impedance-matching. The impactor velocity is u_i. The intersection the Hugoniots of the impactor and sample expresses continuity across the boundary of pressure and mass velocity for the point at (P, u_p), denoted by the small circle.

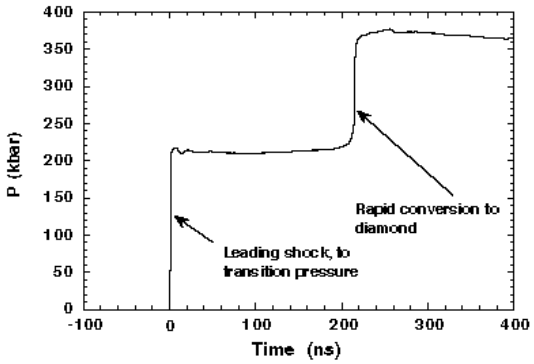

Figure 2: Wave profile for a shock in pyrolytic graphite. The shock is parallel to the c-axis. The step in the leading edge indicates the martensitic graphite-diamond phase transition.

to an absolute accuracy of $\approx 0.1\%$. In many high-explosive experiments, the free-flight distance is too small to permit these methods. In that case, spaced pins are used which protrude through the sample to measure the projectile velocity by contact. When the impact is between dissimilar materials, we must know the Hugoniots of the two materials. Since P and u_p are continuous across the interface, the Hugoniots of each material will intersect in the P–u_p plane at a point which satisfies Eq. 1 for each material. This is depicted graphically in Fig. 1 by the intersection inside the small circle. Finally, if the sample has an unknown Hugoniot, a measurement of the shock velocity in the sample provides the necessary additional information to find u_p. In this case the intersection is between the known impactor Hugoniot and a line of slope $\rho_0 u_s$ (in the sample). These methods are the basis for determination of the Hugoniot equation of state of solids and liquids.

The motion of the interface between two shocked materials may also carry important additional information. The elastic and plastic properties of the material behind the interface between a sample and transparent window can be studied by recording the velocity history (wave profile) of the interface as a shock traverses the assembly. Such records are used to determine elastic limits, phase transition behavior, the effects of release waves, and many other phenomena. Usually a form of laser interferometry is used, and the motion of the interface is determined by measuring the time-varying Doppler shift of a laser source.[3] For example, we show in Fig. 2 the wave profile of a shock generated in pyrolytic graphite.[4] The step in the leading edge indicates the graphite-diamond phase transition. Two such measurements carried out at different levels in a sample will yield the values of u_s, u_p, and the wave profiles. This allows a solution to Eqs. 1–3 to determine the final state parameters.

3 Measuring Shock Velocity

Shock velocities are usually measured using electric or optical methods. As an example of the electrical method, we will describe the method developed by Mitchell,[5] since it is both intuitive and produces highly accurate results. In this method, shock arrival at two planes on the rear surface of a sample is detected by electrical shorting pins in contact with the sample. With most impact experiments, the shock can be made steady, so for an inter-plane distance and time of Δx and Δt, respectively, $u_s = \Delta x/\Delta t$. The value of Δx is usually found using some form of interferometric system to provide better than 1 μm accuracy over mm dimensions. The pins are arranged in two circular arrays of six pins, with an additional pin on the center, as shown in Fig. 3. When a planar shock arrives with tilt angle θ and with angular phase ϕ relative to the array, it introduces a time

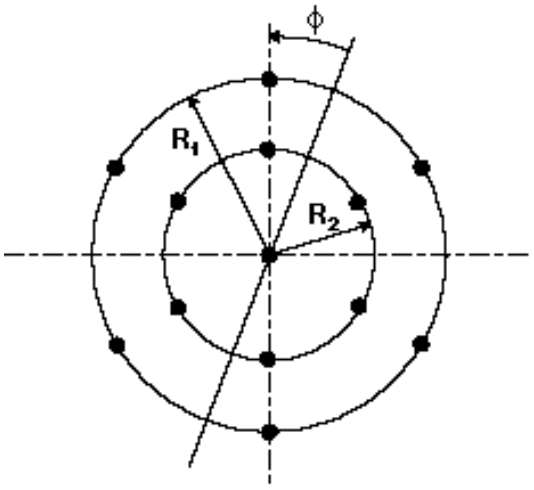

Figure 3: Layout of pin circles for shock velocity measurements. 13 pins are arranged in two circular arrays of radius R_1 and R_2 of six pins each and a centered pin. The two arrays are located on two stepped planes on the rear surface of the target, and the centered pin is on the same level as the outer pin circle. The shock arrives with phase ϕ.

delay across the outer pin circle $\tau = R_1 \sin\theta/u_s$. The arrival times of the pins on the two circular arrays vary as $\tau\cos(\pi n/3+\phi)$ for the outer array, and $\Delta t + (R_2/R_1)\tau\cos(\pi n/3+\phi)$ for the inner array, where $n = (1, 2, \cdots, 6)$ refers to the pin locations on the arrays. Least-squares fitting is used to find the values of τ and ϕ. An attractive feature of this method is that each pair of opposed pins have the same average shock arrival time, which allows a simple check of the consistency of the data. The center pin is used to correct for the typically small parabolic distortions of the impactors in high-velocity gun experiments.[6] In practice, fast oscilloscopes with real-time sweep calibration or digitizers can be used to record shock arrival signals with an accuracy of ≤ 0.5 ns, leading to overall accuracies in shock velocity of typically 0.5 %.

In recent years, we have developed optical methods of performing the same kind of measurement using fast electronic streak cameras. The method is a hybrid between the technique initially developed for laser shock experiments[7] and the pin methods with corrections for tilt and distortion. In this method, we use light generated at or behind the shock front to detect shock arrival. Instead of circular arrays, we record the image of the shock arrival across a diameter of the sample. In the case of strong shocks or highly porous materials, the light emitted by the shocked sample is sufficient,[8] and in other cases an indicator fluid such as benzene or bromoform can be used in contact with the sample rear surface. At pressures above about 10 GPa, these hydrocarbons react and dissociate, have temperatures of ≥ 2500 K, and are efficient light sources. The streak camera used must have a real-time sweep calibration, which we have performed using mode-locked Ar^+ lasers. These methods have the advantage in that they allow very compact samples, no contact is needed with the sample, and that they are at least as accurate as pin methods.

4 Temperature Measurements

As we noted above, Eq. 3 does not yield information about the temperature of the shocked material, yet temperature is an explicit variable in many models of material response at extreme conditions. The temperature of a shocked material is extremely sensitive to phase changes, chemical reactions, dissociation, ionization, and so on. It is of vital importance in understanding the state of the shocked material. For most shocked materials, the temperature is unknown, but significant progress has been made during the last decade. The short time scale of shock experiments, typically less than 10^{-6} s, make electrical measurements impractical, so we employ optical methods. We assume that the emission is of grey-body character, and spectroscopic measurements usually confirm this. This means that measurements of the radiance of the shocked material at multiple wavelengths can be used to determine the temperature using the Planck formula:

$$I(\lambda) = \epsilon\frac{2\pi hc^2}{\lambda^5}\left(\exp\frac{hc}{\lambda k_B T} - 1\right)^{-1}, \qquad (4)$$

where I is the radiance, ϵ is the emissivity, λ is the wavelength, T the (Kelvin) temperature, h is Planck's constant, c the velocity of light, and k_B is Boltzmann's constant. This is rather simple to perform in initially transparent materials, since the material ahead of the shock front does not interfere with the measurement, and the emission can be recorded in real time as the shock traverses the sample. While imaging systems have traditionally been used to collect and record the

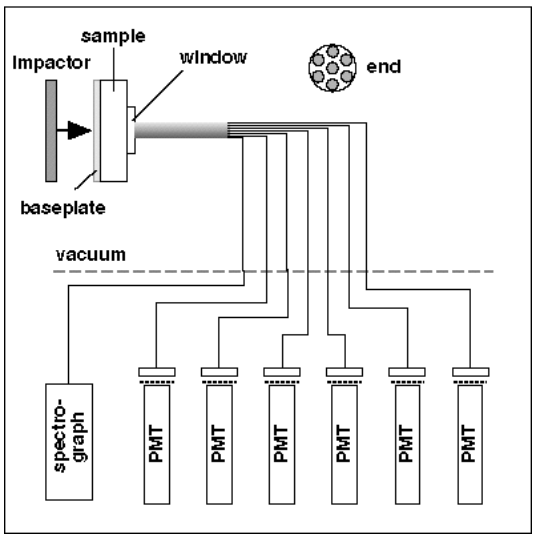

Figure 4: Optical pyrometer for shock experiments featuring fiber-optic coupling to an array of detectors.

shock emission, the use of fiber-optic methods developed by Holmes provide increased sensitivity, time-resolution, and eliminates geometric effects which can obscure the time dependence of the emission.[9] This is shown schematically in Fig. 4 When calibrated against a radiance standard, such as a tungsten (W) ribbon lamp, it is possible to determine the temperature and the emissivity of the shocked material. However, it is important to note that any variations of emissivity with wavelength at these extreme conditions have to be determined by other means. When one desires to determine the temperature of an opaque material, such as a metal, the situation is much more complicated. In this case, the temperature is measured at the interface between a window and the metal. Since the interaction of the shock with the window will generally alter the pressure and temperature, corrections must be included. Furthermore, heat conduction across the interface can introduce yet another uncertainty. Even so, this method has proven valuable to determine, for example, the melting temperature of Fe at Earth core conditions.[10]

Acknowledgments

I am indebted to my colleagues at Livermore and elsewhere for teaching me about the methods and challenges of shock physics. In particular, special thanks are due W. J. Nellis, A. C. Mitchell, and R. J. Trainor. This work was performed by Lawrence Livermore National Laboratory under the auspices of the U. S. Department of Energy under Contract No. W-7405-ENG-48.

References

1. see, for example, D. Bernstein, C. Godfrey, A. Klein, and W. Shimin, *Behavior of Dense Media Under High Dynamic Pressures*, Gordon and Breach (New York, 1968); François Bauer, in *Shock Waves in Condensed Matter*, Y. M. Gupta, ed. Plenum (New York, 1986, p. 483 ff.
2. A. C. Mitchell and W. J. Nellis, *Rev. Sci. Instrumen.* **52**, 347 (1981).
3. L. M. Barker and R. E. Hollenbach, *J. Appl. Phys.* **43**, 4669 (1972).
4. D. J. Erskine and W. J. Nellis, *Nature* **349**, 317 (1991).
5. A. C. Mitchell and W. J. Nellis, *J. Apl. Phys.* **52**, 3363 (1981).
6. A. C. Mitchell and W. J. Nellis, *Rev. Sci. Instrumen.* **52**, 347 (1981).
7. L. Veeser and J. Solem, *Phys. Rev. Lett* **40**, 1391 (1978).
8. N. C. Holmes, *Rev. Sci. Instrum.* **62**, 1990 (1991).
9. N. C. Holmes, *Rev. Sci. Instrum.* **66**, 2615(1995).
10. C.S. Yoo, N.C. Holmes, M. Ross, D.J. Webb, and C. Pike, *Phys. Rev. Lett.* **70**, 3931(1993).

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